

SYSTEM AND METHOD TO MINIMIZE THE AMOUNT OF NO_x EMISSIONS BY
OPTIMIZING THE AMOUNT OF SUPPLIED REDUCTANT

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The present application incorporates by reference, in its entirety and for all purposes, the entire contents of serial number _____, filed _____, assigned to the same assignee as the present application, titled , "SYSTEM AND METHOD TO MINIMIZE
10 THE AMOUNT OF NO_x RELEASED FROM A NO_x TRAP", attorney docket FGT.3A8 (202-1552).

Background and Summary of the Invention

In a vehicle having an internal combustion engine, it can
15 be beneficial to have an emission control system capable of storing NO_x. The control of emitted NO_x is particularly important when the engine is operating lean. While lean operation improves fuel economy, the exhaust during lean operation may contain increased amounts of excess oxygen for extended periods of time,
20 thereby affecting NO_x conversion of three way catalysts.

Emission control devices capable of storing NO_x during lean operating conditions (NO_x traps) can be used to store the generated NO_x. Periodically, as the NO_x capacity of a NO_x trap is approached, the air-fuel ratio (A/F ratio) can be driven to a rich

condition for a period to convert at least a portion of the stored NO_x and regenerate the NO_x storage capacity of the trap. This can be referred to as NO_x trap purging.

In addition to storing NO_x during lean/rich cycling, the NO_x traps may also provide HC, CO, and NO_x conversion when the A/F ratio is controlled about stoichiometry. This is beneficial, for example, during high load operation. If NO_x traps contain low amounts of oxygen storage capacity (OSC), the ability of these catalysts to convert CO and NO_x under the oscillatory A/F conditions characteristic of closed-loop control systems can be limited. To provide three-way conversion in this oscillatory environment, NO_x traps often contain oxides of cerium or mixed oxides of cerium and zirconium. In addition, the cerium may provide OSC during lean operating conditions and release oxygen during the rich operation to providing oxidants for converting the HC and CO.

The inventors herein have recognized that the inclusion of cerium in a NO_x trap may also have disadvantages effects on NO_x emission control. Among these effects are that cerium may require additional reductants during the rich operation purges (e.g., to reduce stored oxygen due to the OSC provided by the cerium), and that during a purge the OSC provided by cerium may cause some of the stored NO_x to be released from the trap without being reduced to N₂. This purge NO_x release may be particularly

evident at temperatures of 350°C and above, and may increase as the amount of stored NO_x is increased.

Thus, the inventors herein have recognized that NO_x emission control systems based on NO_x trap storage efficiency or storage capacity may be ineffective at reducing NO_x emissions, and specifically, that NO_x tailpipe emissions during a rich purge may be attributed to an inadequate concentration of reductants being supplied due in part to the OSC element within the NO_x trap.

The above disadvantage can be overcome by a method for controlling an engine having an exhaust with an emission control device capable of storing NO_x during lean operating conditions, and converting at least a portion of said NO_x during stoichiometric or rich operating conditions, the method comprising:

operating the engine to produce a lean exhaust gas mixture fed to the emission control device;

after said lean operation, operating the engine to produce a rich exhaust gas mixture fed to the emission control device, said rich air-fuel ratio determined as a function of at least the oxygen storage capacity of the device.

Thus the inventors herein have recognized that the NO_x emitted from a NO_x trap during a rich purge may be further reduced by correlating the level of reductants in the rich air-gas mixture to the NO_x trap's OSC. Note that the OSC of the NO_x trap will vary over the life of the NO_x trap due to various influences including

thermal degradation, cerium deterioration, sulfur degradation, and desulfation operation. As trap OSC decreases with age the magnitude of the purge reductants may be decreased while still limiting the purge NO_x release.

5 In another aspect, the above disadvantage can be overcome by a computer storage medium having instructions encoded therein for controlling an engine having an exhaust with an emission control device capable of storing NO_x during lean operating conditions, and converting at least a portion of said NO_x during stoichiometric or
10 rich operating conditions, said medium comprising:

code for operating the engine to produce a lean exhaust gas mixture fed to the emission control device;

after said lean operation, code for operating the engine to produce a rich exhaust gas mixture fed to the emission control
15 device, said rich air-fuel ratio determined as a function of at least the oxygen storage capacity of the device.

Further, the inventors herein have also recognized that, several other factors besides the level of supplied reductants influence the amount of NO_x released from NO_x trap during a purge.
20 These factors include the amount of NO_x stored, the OSC of the trap, and the trap temperature. All these factors can be considered in order to reduce the amount of emitted NO_x. Thus, the inventors have discerned that NO_x trap purging can be improved when the engine operates to produce a rich air-fuel ratio selected to provide a

level of reductant dependent on the trap temperature and trap OSC.

Brief Description of the Drawings

5 The advantages described herein will be more fully understood by reading examples of embodiments in which the invention is used to advantage, with reference to the drawings, wherein:

Figure 1 is a block diagram of an engine in which the
10 invention is used to advantage;

Figures 2 and 3 are exemplary routines for controlling an engine having an emission control device capable of storing NO_x under lean operating conditions; and

Figures 4 through 11 are graphs of experimental
15 results involving NO_x emission control devices.

Description of Example Embodiment(s)

Referring to Figure 1, an internal combustion engine 10 may
20 include at least one emission control devices capable of storing NO_x during lean operating conditions. Engine 10 includes combustion chamber 30 and cylinder walls 32 with piston 36 positioned therein and connected to crankshaft 13. Combustion chamber 30 communicates with intake manifold 44 and exhaust

manifold 48 via respective intake valve 52 and exhaust valve 54. Exhaust gas oxygen sensor 16 is coupled to exhaust manifold 48 of engine 10 upstream of catalytic converter 20. A HEGO, UEGO, or exhaust gas NO_x sensor 18 is coupled to the exhaust manifold 5 48 upstream of NO_x trap 22, and a second HEGO, UEGO, or NO_x sensor 24 is coupled to manifold 48 downstream of NO_x trap 22.

Intake manifold 44 communicates with throttle body 64 via throttle plate 66. Throttle plate 66 is controlled by electric motor 67, which receives a signal from ETC driver 69. ETC driver 10 69 receives control signal (DC) from controller 12. Intake manifold 44 is also shown having fuel injector 68 coupled thereto for delivering fuel in proportion to the pulse width of signal (fpw) from controller 12. Fuel is delivered to fuel injector 68 by a fuel system (not shown) including a fuel tank, 15 fuel pump, and fuel rail (not shown).

Engine 10 further includes distributorless ignition system 88 to provide ignition spark to combustion chamber 30 via spark plug 92 in response to controller 12. In the embodiment described herein, controller 12 is a microcomputer including: 20 microprocessor unit 102, input/output ports 104, electronic memory chip 106, which is an electronically programmable memory in this particular example, random access memory 108, and a data bus.

Controller 12 receives various signals from sensors coupled to engine 10, in addition to those signals previously discussed, including: measurements of inducted mass air flow (MAF) from mass air flow sensor 110 coupled to throttle body 64; engine
5 coolant temperature (ECT) from temperature sensor 112 coupled to cooling jacket 114; a measurement of throttle position (TP) from throttle position sensor 117 coupled to throttle plate 66; a measurement of turbine speed (Wt) from turbine speed sensor 119, a profile ignition pickup signal (PIP) from Hall effect sensor
10 118 coupled to crankshaft 13 indicating engine speed (N); and an optional sensor to detect feedgas NO_x concentration (not shown).

Continuing with Figure 1, accelerator pedal 130 is shown communicating with the driver's foot 132. Accelerator pedal
15 position (PP) is measured by pedal position sensor 134 and sent to controller 12.

In an alternative embodiment, where an electronically controlled throttle is not used, an air bypass valve (not shown) can be installed to allow a controlled amount of air to bypass
20 throttle plate 62. In this alternative embodiment, the air bypass valve (not shown) receives a control signal (not shown) from controller 12.

As will be appreciated by one of ordinary skill in the art, the specific routines described below in the flowcharts may

represent one or more of any number of processing strategies such as event-driven, interrupt-driven, multi-tasking, multi-threading, and the like. As such, various steps or functions illustrated may be performed in the sequence illustrated, in parallel, or in some cases omitted. Likewise, the order of processing is not necessarily required to achieve the features and advantages of the invention, but is provided for ease of illustration and description. Although not explicitly illustrated, one of ordinary skill in the art will recognize that one or more of the illustrated steps or functions may be repeatedly performed depending on the particular strategy being used. Further, these Figures graphically represent code to be programmed into the computer readable storage medium in controller 12.

Referring now to Figure 2, a routine is described for controlling an engine having an emission control device capable of storing NO_x under lean operating conditions such as a NO_x trap. First, in step 210, the routine determines whether the engine is operating under lean conditions. For example, the routine determines whether the engine is operating at an A/F ratio of greater than stoichiometric mixture of 14.6 to 1.

Next, in step 212, the routine determines the OSC of the NO_x trap. This can be determined in a variety of ways. For example, the amount of OSC in the trap can be estimated from the

difference in switch times during the previous rich-to-lean transition. Alternatively, an average of several previous transitions can be used. In step 214 the routine then determines the A/F ratio to be supplied during a rich purge
5 based on the OSC. Then, following a duration of time determined by operating conditions, in step 216, the routine ends lean operation and operates the engine to produce a rich A/F exhaust gas mixture according to the OSC-determined A/F ratio.

Figure 3 describes an alternative routine for controlling
10 emissions from an engine having a NO_x trap. In step 310, the routine determines if the engine is operating under lean conditions, in step 312, the routine determines the OSC of the NO_x trap, and in step 314 the routine determines the temperature of the NO_x trap. NO_x trap temperature can be determined in a
15 variety of ways including measured directly using a thermocouple (or other temperature measurement device) or estimated from a temperature model.

In step 316, the routine determines a rich A/F ratio to be supplied during an upcoming purge based on NO_x trap OSC and
20 temperature. In step 318 the routine ends lean operation and operates the engine to produce a rich A/F exhaust gas mixture according to the OSC and temperature determined A/F ratio. Thus, in the routine of Figure 3 the A/F ratio supplied in a

rich purge is based on both the OSC and temperature of a NO_x trap.

The inventors performed a number of experiments on NO_x traps. These experimental results revealed the complex relationships between NO_x trap OSC, the concentration of reductant supplied in a rich purge, the NO_x trap temperature, and the amount of NO_x emitted during a purge. Such data can be used in the determinations and calculations described above with respect to Figure 2 and 3. Figures 4-12 summarize these experimental findings.

Figure 4 is a graph of the NO_x Efficiency versus lambda value at 500°C for NO_x traps with and without cerium after high temperature aging. This shows that a NO_x trap containing cerium had much better NO_x conversion at stoichiometry (lambda = 1.0) than a trap without cerium after the traps were aged on a high temperature schedule with maximum temperatures near 1000°C. Therefore, the NO_x trap itself may contain some OSC in order to provide high CO and NO_x conversion under these conditions.

Figures 5 and 6 further show example effects of including OSC in a NO_x trap. These figures depict the results from experiments comparing the NO_x release for a stabilized trap with no oxygen storage capacity and a stabilized trap containing oxygen storage capacity. Figure 5 shows that when these traps were evaluated at 350°C using a 5 minute lean/3 minute rich

cycle the trap without OSC was less effective at storing NO_x during the 5 minute lean period, but it exhibited much less NO_x release during the purge than the trap containing OSC.

Figure 6 shows the percent NO_x release at different temperatures for the NO_x traps with and without OSC. In this experiment the amount of NO_x stored during the lean period and the amount of NO_x released during the rich period were calculated, and the amount of NO_x release was then determined as a percentage of the amount of NO_x stored. For both NO_x traps, the percent NO_x release generally increased as the temperature increased beyond 350°C. As can be seen the trap with OSC had a significantly higher percentage of NO_x release than the trap without OSC at these higher temperatures. Figure 6 clearly indicates that the percentage of NO_x release depends on the temperature and the oxygen storage capacity of the trap.

Figure 7 reveals that the amount of NO_x release is also a function of the amount of reductant supplied to the trap during the purge. A NO_x trap pre-conditioned at 600°C was evaluated for NO_x storage and NO_x release at 500°C using a test cycle with a lean period of two minutes and a rich period of one minute. The CO level during the rich purges was varied from 0.5 % to 13 %. Figure 7 shows the tailpipe NO_x for these tests with the different purge CO levels. The amount of NO_x release decreased significantly as the purge CO level increased. This shows that

the amount of NO_x release can be decreased by providing higher concentrations of reductant during the purges (i.e., by using richer A/F ratios during the purges). As shown by Figure 6 above, the amount of reductant needed to minimize the NO_x release can be advantageously determined based on the temperature and the level of OSC in the trap.

Studies were performed on NO_x traps that contained different amounts of a ceria-containing mixed oxide. After stabilization at 600°C, samples of these traps were evaluated for oxygen storage capacity at different temperatures. In this study the sample was reduced for 30 seconds in 1 % CO and then oxidized for 30 seconds in 0.5 % O₂. The total OSC was determined from the amount of oxygen taken up during the 30 second lean period and normalized by the weight of the sample. The "fast" OSC was defined as the amount of oxygen taken up by the trap before any breakthrough of oxygen occurred. Oxygen storage tests were also performed on samples of these traps that had been aged for 50 hours on a high temperature aging cycle with maximum temperatures of 1000°C. In Figure 8 the fast OSC results were taken for the fresh and aged samples at 425°C. Either type of catalyst can be used herein. Note that this also illustrates optional advantages that can be obtained by tracking OSC over the life of the catalyst as the OSC changes with aging.

Figure 9 is a graph of NO_x release versus purge CO level on a 2/1 cycle at 425°C for stabilized NO_x traps with different levels of mixed oxide. During this experiment samples of traps stabilized at 600°C were evaluated for NO_x storage and NO_x release at 425°C by utilizing the 2/1 cycle. The CO level during the rich purges was varied from as low as 0.5 % to as high as 16 %. During the purges, the feedgas also contained H₂ at 1/3 of the CO level to reflect the approximate ratio of these species in actual engine exhaust. The amount of NO_x storage was relatively constant at around 12-13 mg/in³ for these tests, and the amount of NO_x release was calculated for the different levels of CO and normalized by the volume of the sample. Figure 9 shows the amount of NO_x release as a function of the purge CO level for samples with 0 % and 75 % mixed oxide (MO), which had oxygen storage levels of 8 and 103 micromoles O/gram of trap. For a given level of CO, the sample with 0% MO had much lower NO_x release than the sample with 75% MO. Thus, a much higher level of CO may be used for the high OSC trap to achieve the same NO_x release as the low OSC trap.

Figure 10 is a graph of data from the same study on samples with 0, 12, 37, and 75% MO. The data for these four traps were analyzed to determine the amount of CO supplied to achieve specified levels of NO_x release. Figure 10 shows the CO required to achieve NO_x release levels of 0.2, 0.4, 0.6, 0.8, and 1.0

mg/in³ as a function of the measured OSC of the sample. As such, to achieve a relatively constant level of purge NO_x release, less reductant is required as the OSC of the trap decreases.

- 5 Figure 11 demonstrates that similar OSC and NO_x release results were obtained at a temperature of 500°C. A permissible level of NO_x release may be specified so that the required level of CO can be determined for the different levels of OSC. As an example, in Figure 11 a level of 0.6 mg/in³ was specified.
- 10 Figure 11 shows the CO required to achieve a NO_x release of 0.6 mg/in³ at both 425°C and 500 C. For a given level of OSC, much more CO is required at 500°C than at 425°C to achieve the 0.6 mg/in³ of NO_x release.

 Thus, this data can be used to generate tables, in one
15 example, to be used during engine control to select (during real-time operation) a level of reductant (or a level of a rich air-fuel ratio) to be provided during a NO_x purge. Further, the rich level can be varied during the rich purge to provide a desired profile suited to expected NO_x release. Also, the rich
20 air-fuel ratio can be selected based on a change in OSC determined from diagnostic routines detecting catalyst degradation based on changes in switching times (or switch ratios, for example) of exhaust gas oxygen sensors. Further, these determinations of degradation can be based on an amount of

sulfur retained in the device. Note also that when determining OSC, OSC is somewhat sensitive to sulfur, but thermal degradation may be a larger cause of reducing OSC.

As described in the examples above, the amount of OSC in the trap can be estimated from the difference in switch times during the rich-to-lean transition. The bed temperature of the LNT can be measured using a thermocouple or estimated from a temperature model. The bed temperature and the measured amount of OSC can be used with Figure 11 to determine the amount of CO necessary to limit the NOX release to a specified level (which can be selected to vary depending on operating conditions), which is 0.6 mg/in³ in this example. For fresh or stabilized traps that have high levels of OSC, significantly richer purges can be necessary to limit the purge NOX release to the desired level. However, as the trap ages and the OSC decreases, the magnitude of the purge can be decreased while still limiting the purge NOX release. Also, the system can operate in both a stoichiometric mode and a lean burn mode, where the NOx trap contains some OSC.

This concludes the description of the invention. The reading of it by those skilled in the art would bring to mind many alterations and modifications without departing from the spirit and the scope of the invention. Accordingly, it is

intended that the scope of the invention be defined by the following claims: